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Test Results of the Terminal Air Traffic Control Laboratory System

TECHNICAL MEMORANDUM

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Test Results of the

Terminal Air Traffic Control Laboratory System

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DEVELOPMENT
CORPORATION
2500 COLORADO AVE.
SANTA MONICA
CALIFORNIA

23 September 1963

Terminal Air Traffic Control Laboratory System

in Operation

Handovers of inbound and outbound aircraft are coordinated between the local controllers (foreground) and the conversion controllers (background) by the traffic coordinator (not shown).

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TEST RESULTS OF THE TERMINAL AIR TRAFFIC CONTROL LABORATORY SYSTEM

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1. INTRODUCTION

System design is still an art. As an art, the processes of conceptualizing a system, choosing the component pieces, and putting them together depend upon the experience and intuition of a group of experts. If there is ever to be a science of systems, one of the prerequisites is a methodology through which system phenomena can be reproduced in the laboratory for scientific study.

The Terminal Air Traffic Control (TATC) project was based on the premise that significant facts can be discovered about how systems operate by putting an entire system* in the laboratory, simulating a task environment with which it would interact, and watching it operate. In this technique, at first, there is no systematic attempt to abstract either the system components or the system operations. Instead, we chose to study first the problem of how to design a computer-based terminal air traffic control system. By designing and manipulating a laboratory model of such a system we hoped to uncover not only problems of information transmission between men and computers in an operational situation, but also the attendant problems of simulating real-time, man-computer systems rapidly and with least cost.

2. TEST OBJECTIVES

At the outset of the TATC project, a minimal system consisting of the control agencies at one airport terminal was modeled in System Development Corporation's Systems Simulation Research Laboratory. This initial system

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* The problem of what constitutes an adequate system for study by this method is a matter for much argument. In this context we are reminded of an observation, attributed to Dr. Milton Weiner of RAND, that "one man's system is another man's subsystem." Techniques have been devised for embedding the laboratory experimental system in a larger organizational context with which it interacts. We do not intend to address the problem of what the size of the experimental system should be except to provide a cookbook formula, viz., as large as possible subject to the capability of the experimenter to control the environment within which the system operates as constrained by laboratory space and computer capacity.

served primarily as an exploratory device. Some of the system design objectives and a description of the system are presented in TM-639/002/00. The present paper discusses the results of the system shakedown tests performed during the summer of 1962.

After computer program testing was completed in the spring of 1962, a live shakedown and familiarization test was run. This test, in addition to extending the program checkout to the more complex live situation, was intended to familiarize the system designers and researchers with the system by letting them observe it in operation under a variety of environmental conditions. To complement this "naturalistic" observation, three general questions were posed: (1) What is the capability of the system to control air traffic? (2) How sensitive is the system to a variety of traffic and procedural conditions? (3) Do the computer programs or hardware restrict the performance of the operators?

3. THE LABORATORY SYSTEM

The laboratory system was modeled after the San Francisco-Oakland geographic area. This geographic area measures 100 by 130 nautical miles and extends 4 nautical miles high. Within this volume, the airport was responsible for two cylinders of airspace called the conversion zone and the local area (see Figure 1).

A distinction was made between the "test system" and the "embedding system." The test system consisted of two subsystems: conversion control and local control. The conversion control subsystem, consisting of two controllers, was responsbile for all aircraft in transition between the en route phase and the final approach or initial departure phases. The local control subsystem, consisting of a traffic coordinator, and two other controllers, was responsible for approaches and departures. Communications between these subsystems were via a flight data processor, the computer. It is this test system which was manipulated and analyzed. The embedding system consisted of surrounding agencies with which the test system communicated. It included two ground controllers, two sector controllers, and up to seven pilots. The environment of the test system was controlled through the embedding system.

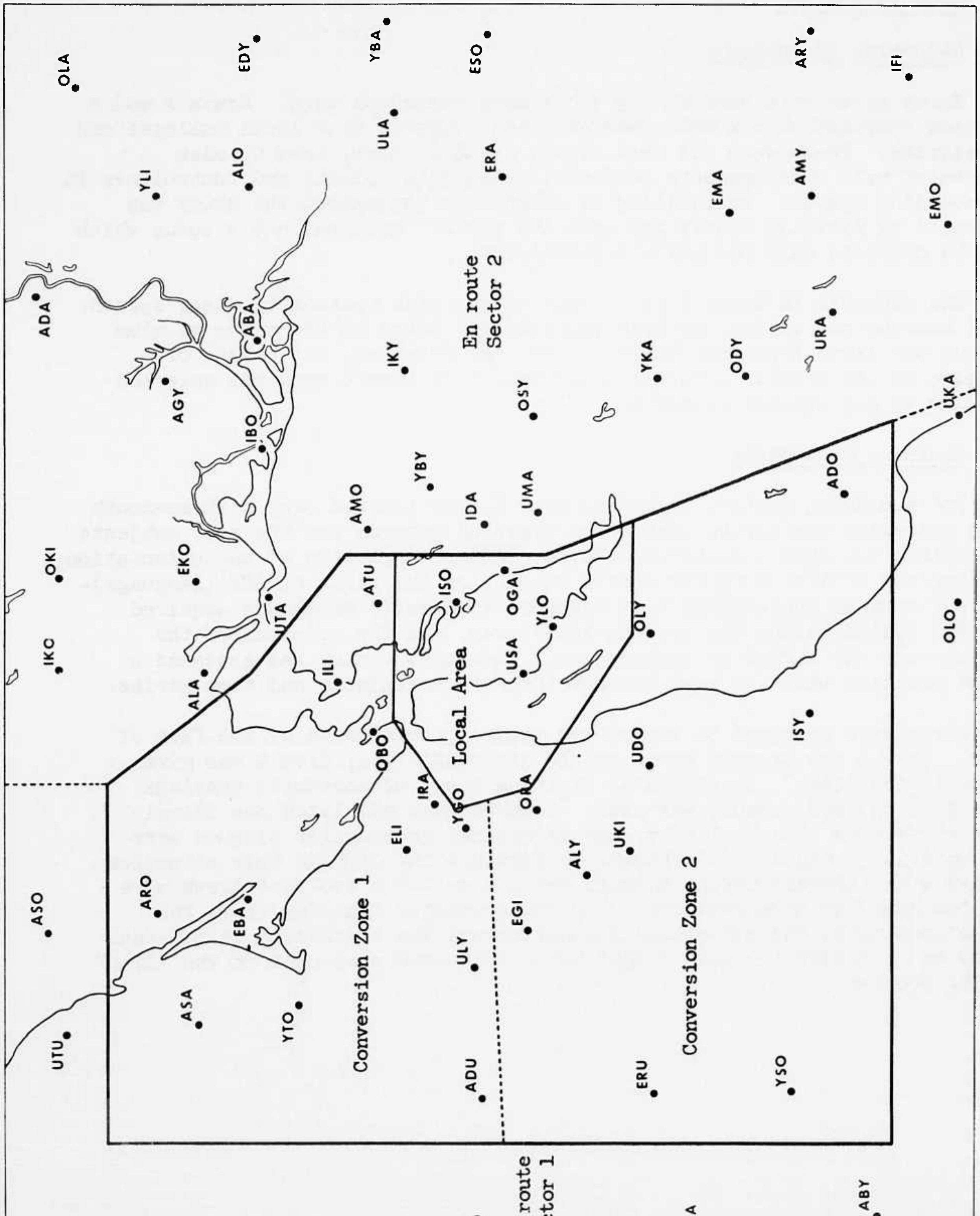

Fig. 1.--TATC geography

4. TEST PROCEDURES

4.1. Selection of Subjects

Three crews were used during the summer shakedown test. Crews A and B were each composed of six male undergraduate students from local colleges and universities. These were the test crews. A third crew, Crew C, also composed of male undergraduate students, operated as pilots and controllers in the embedding system. Probability of attendance throughout the study was encouraged by dividing hourly pay into two parts: base pay and a bonus which could be received only for perfect attendance.

The subjects in Crews A and B were chosen with reasonably clear speech, normal hearing and vision, an intelligence test score in the range of plus or minus one sigma from mean score for college freshmen, and a lack of knowledge of air traffic control. The members of Crew C were not selected according to any special criteria.

4.2. Training Procedures

The embedding system, including Crew C, was trained over a three-month period preceding the system test. The training program for the test subjects began with a one-week orientation course. After completion of the orientation, the group was divided into two crews, matched on the basis of ACE (Language)-centile scores, an achievement test designed to measure knowledge acquired about the system during the orientation course, and the opinions of the experimenters who served as instructors. Each crew member was assigned a control position which he kept through the entire training and test series.

Crews were assigned to one of two training treatments by the flip of a coin. Crew A was trained under on-the-job conditions; Crew B was given "schematic training." In schematic training a set of schematic drawings of the face of each console was used. Colored pegs simulated the illumination of various console lights, and magnetized rectangular plaques were moved on a large magnetic blackboard to simulate the GEOPLAN (air situation display) with aircraft moving through the system. The two test crews were given the same training problems. For the schematic training crew, the instructions moved the magnetized plaques across the blackboard in non-real time so as to follow the same flight paths that were presented in the "live" training problem.

4.3. Training Problems

Except for the first problem, which was a one-hour problem, each training problem lasted two hours. The problems were divided into 30-minute segments, each designed to present at least two or three air situations which stressed at least one important control procedure, e.g., an emergency procedure, a change in flight plan procedure, or a handover procedure. In addition, the problems were designed to gradually increase traffic load, rate of input, and traffic mix or heterogeneity (i.e., aircraft which differed markedly in performance). Altogether, training and orientation lasted five weeks.

4.4. Test Design

The system was tested with 24 two-hour problems involving a total of 960 aircraft. The test was designed as a factorial combination of four variables. Three of the variables describe the traffic characteristics; the fourth was procedural.

1. Input Rate: the rate at which inbound aircraft penetrate the system. Two values were used: (1) uniform and (2) non-uniform. For the uniform rate, aircraft were scheduled to enter the system about every 2-1/2 minutes over a 13-minute interval; for the non-uniform rate, an equivalent number of inbounds were scheduled to penetrate the system in a 7-minute interval, with two-thirds of the aircraft penetrating during the middle 4-minutes. The number of outbounds was held constant.

2. Distribution: the geographic distribution of the inbound aircraft between the two conversion zones (see Figure 1). Three values were used: (1) equal distribution, (2) north greater, (3) south greater. Where the distribution was not equal, one zone received twice as many aircraft as the other.

3. Composition: this refers to the performance characteristics of the aircraft in the traffic sample.* Two values were used: (1) heterogeneous, (2) homogeneous. In the homogeneous case, all aircraft were high performance, such as a commercial jet; in the heterogeneous case, the aircraft were evenly divided between medium performance, such as a DC-7, and supersonic.

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* These data were obtained from L. Farr and H. Schmitz, "An Estimate of the 1970-1975 Environment for Air Traffic Control," TM-599/000/01.

4. Configuration: the two procedures followed by the crews--configurations I and II. In configuration I the flight plans for an aircraft included at least three fixes between the point at which the system was penetrated and the airport; in configuration II, no intermediate fixes were specified. Also, separation standards in the local area were lower for configuration II than for configuration I.

The variables of input rate and distribution represented uniform and non-uniform dispersion of aircraft in time and in space; the composition variable represented uniform and non-uniform dispersions of system transition times. The configuration variable required directed or opportunistic responses of the system.

Each combination of variables gave rise to a traffic schedule for one "problem period." A problem period was designed to last 30 minutes. During that time, six inbound and four outbound flights were scheduled. A flight remained within the system for about 15 minutes on the average. The first 12 problem periods, corresponding to the following cells in the factorial design, were under configuration I, as in Figure 2.

Order	Input Rate	Distribution	Composition	Configuration
1	1	1	2	I
2	2	2	1	I
3	1	3	2	I
4	2	2	2	I
5	2	3	1	I
6	1	2	2	I
7	2	1	2	I
8	1	1	1	I
9	1	3	1	I
10	2	3	2	I
11	2	1	1	I
12	1	2	1	I

Fig. 2.--Factorial combination of variables

The next 12 replicated the first 12. The last 24 repeated the first 24 except that configuration II was used instead of configuration I. Each of the two crews was presented with the same sequence of problem periods. A crew ran for approximately two hours every other day, a run consisting of four problem periods.

4.5. Problem Design

Twelve standard sets of flight paths were generated, one for each of the unique combinations of the traffic variables. In preparing the schedule for a problem period, these flight paths were translated into flight plans according to the starting time of the particular problem period. Since part of the system design was based on the assumption of a central scheduling function which guaranteed flight plans to be free of conflict at fixes, the standard flight paths were processed by a computer program which resolved such conflicts by revising altitude assignments. The output from this conflict resolution program was examined manually and adjusted further where necessary to conform as closely as possible to the standard paths. Then flight-plan strips were printed automatically for the subjects and for simulators, observers, and experimenters. Certain parameters of these flight plans were used by another computer program to produce a control deck of punched cards which supplied all the necessary information which the computer programs in the test and embedding systems needed to "create" these flights.

4.6. Data Collection

Observation and data collection were both direct and indirect. The embedding system operated on a balcony surrounding the test room and separated from it by one-way glass. This permitted direct visual observation of the test crews. In addition, direct observation of communications was possible by means of microphones in the test room and by means of monitor speakers connected to the simulated radio system and intercom system. Indirect observations were made from duplicates of the displays used by the test system and from deductions based on information displayed to pilots and the ground and sector control simulators. Similarly, the direct data collection consisted of such items as tape recordings of conversations and discussions, polygraph recordings of selected switch actions, and notes taken about interesting or unusual situations. The indirect data collection was based upon a record that was kept by the computer of every switch action taken, as well as selected tables of information. These recordings were made every few seconds. From the magnetic tape recordings of the switch actions, the entire run could be re-created by the computer program, playing back the taped switch actions instead of using live switch insertions. Aircraft histories were constructed directly from the recorded selected tables; these histories formed the basis for deducing further measures of system performance.

4.7. Conduct of a Test Run

A test run started with a briefing of the embedding system by a problem designer. Concurrently, the test crew was holding its own briefing, discussing the flight strips for the first segment of the day's run. Next, the embedding system personnel worked with the computer to check out all equipment components used for man-computer communication; they also checked the radio and the intercom systems. After they had ascertained that all equipment was operating properly, the embedding system personnel took their positions and the test crew was ushered into the test room. As soon as everyone was ready, the synchronized clocks were started and the run began. When the last aircraft from the last problem period was out of the test system, the run was terminated by a phone call from the supervisor (an experimenter). This was followed by an embedding system debriefing and a concurrent test crew debriefing. The test crew debriefing was in two parts. In the first part, which was unsupervised, the crew discussed their performance in the run just completed. In the second part, led by a researcher, the crew received a report of their errors, which they discussed. The researcher discussed procedures with them and tried to get them to evaluate the system design and make suggestions. Procedural matters which came up in one crew's debriefing were introduced in the other crew's debriefing. The researcher also acted as an intermediary between the crew and the simulated administrative organization constructed above it.

5. MEASURES

There is no single measure by which system performance can be evaluated. Instead, four general categories of measures seem to be significant in air traffic control.

5.1. Categories of Measures

Safety. One of the prime requirements of the system is that it control air traffic safely. Two aspects of safety were measurable: the number of violations of prescribed separation standards between aircraft and the probability that a collision would occur in the immediate future between any pair of aircraft.

Expeditiousness. This is a broad category with many aspects. The performance of the system in expediting the traffic flow was measured by: the per cent of flight time spent holding*; the per cent of controlled

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* Holding an aircraft refers to instructing it to fly in an orbit around a designated point. This represents a delay in proceeding to its destination.

aircraft which are held; the delay imposed on the traffic as compared to a theoretical optimum flow; the ratio of average flight time to the average theoretical flight time; the average time in buffer; and the average transition time.

Orderliness. Within the context of an air traffic control system, order is a difficult concept to pin down. As an end in itself, orderliness cannot be defended. But to the extent that it tends to increase safety, expeditiousness, and economy, it improves the performance of the system. One aspect of orderliness seems particularly significant: the smoothing of the variations in arrival times at the approach buffer. Since the maximum acceptance capability of a runway can be realized only with a flow of traffic regularly spaced in time at the approach gates, with spacing equal to the minimum runway service time, it is advantageous to regulate the traffic to conform to this pattern. The measure of the regulation of the traffic flow is called "smoothing."

Other Measures. We were also interested in developing measures of the cost of system operation, or the efficiency with which resources were utilized. The amount of fuel consumed by an aircraft while under control of the TATC system is such a measure.

5.2. Description of Individual Measures

The separate measures can be described as follows:

Collision Probability. The probability, expressed as a per cent, that a collision will occur while aircraft are under control of the specified system or subsystem.

Safety Violations. The number of times two or more aircraft flew closer than the specified separation limits.

Time Held. The per cent of total time that aircraft under system control spent holding.

Aircraft Held. The per cent of aircraft under system control which were held at least once.

Schedule Delay. The average delay imposed on traffic by the control system; the difference between actual flight time and a theoretical time required to fly the shortest available path from the point of entering upon system control to the point of leaving it. Negative values are possible.

Schedule Ratio. The average ratio of actual to theoretical flight times.

Mean Spacing. The average time between the arrival of aircraft at designated points in the terminal area. In general, a lower value means better performance.

Time in Buffer. The average time that an aircraft spent waiting to be transferred from the conversion control to the local control subsystem.

Transition Time. The average time during which an inbound aircraft was the responsibility of the conversion control subsystem but was not being held in the buffer.

Smoothing. The variability of differences in arrival times at designated points in the terminal area relative to a theoretical uncontrolled traffic flow. Negative values are possible; a more positive value means better performance.

Fuel Consumption. The cost of fuel consumed by an aircraft while under system control.

6. RESULTS

In addition to design verification and program checkout, the test was intended to allow researchers to observe the system and to produce some information about the system's ability to control air traffic, about the sensitivity of the system to varying traffic and procedural conditions, and about the interaction of the operators and the computer via the hardware interface. To this end, measures of system and subsystem performance were applied. They showed some interesting relationships about the way the crews and system reacted to the varying environmental conditions.

Tables 1 through 4 summarize the results of the system test. In these tables, the effect of each of the variables is evaluated with the measures of system performance described in the preceding section.

6.1. Crew Differences

Subjective evaluation of the two crews throughout the test runs showed both inter- and intra-crew differences. In terms of the conversion control subsystem and the local control subsystem, these differences can be summarized as follows:

1. The conversion controllers of Crew A were slightly superior to those of Crew B. There was a greater disparity in performance between controllers in Crew B than in Crew A.

2. In both crews the individual local controllers were roughly comparable; the local control team of Crew A was somewhat better than that of Crew B.

3. The traffic coordinator of Crew A integrated the performance of the other crew members; the traffic coordinator of Crew B was relatively ineffectual.

From these subjective observations of crew characteristics we predicted that Crew A would perform better than Crew B; that inter-crew conversion control differences should be less than local control differences, which in turn should be less than total system differences.

Table 1 shows how the two crews performed. Four points are evident from this table:

1. The performance of the crews differed significantly only as regards the expeditious handling of traffic.

2. There is no significant difference in performance between the conversion control subsystem of the two crews.

3. Crew B performed better than Crew A in only 2 of the 23 measures in the table.

4. On the average, aircraft were held in the buffers about 1.5 times longer by Crew B than Crew A. For arriving aircraft, the buffers are the interface between the two systems in which aircraft form a queue; the conversion control subsystem puts aircraft in and the local control subsystem removes them. The average time that aircraft are held in the buffers is a good measure of the integration of the subsystems.

These results support the subjective evaluation of the crews discussed previously. It is interesting that, in the analysis of variance performed on the data, there were no statistically significant interactions involving the crew variable.

TABLE 1

Crew Effect on System Performance

Measure	Total System			Conversion Control Subsystem			Local Control Subsystem		
	Crew A	Crew B	Sig.*	Crew A	Crew B	Sig.*	Crew A	Crew B	Sig.*
Safety									
Collision Probability(%)	61	70	-	26	26	-	49	59	-
Expeditiousness									
Time Held (%)	6	9	<.01	2	3	-	10	16	<.01
Aircraft Held (%)	39	51	<.01	22	27	-	25	35	<.01
Schedule Delay (sec.)	90	147	<.01	79	84	-	42	88	<.05
Schedule Ratio (%)	115	124	<.01	141	142	-	102	102	-
Time in Buffer (min.)	3.82	6.26	<.01						
Orderliness									
Mean Spacing (sec.)	88.5	90.8	-	100.1	104.3	-	111.2	98.5	-
Smoothing	- 0.62	-0.82	-	-0.16	-0.22	-	-0.40	-0.45	-
Cost									
Fuel Consumption	578.3	564.3	-						

* The significance of the differences between the means shown was determined by an analysis of variance.

TABLE 2

Traffic Composition Effect on System Performance

Measure	Total System			Conversion Control Subsystem			Local Control Subsystem		
	Hetero.	Homogen.	Sig.*	Hetero.	Homogen.	Sig.*	Hetero.	Homogen.	Sig.*
<u>Safety</u>									
Collision Probability(%)	65	67	-	30	22	-	50	57	-
<u>Expeditiousness</u>									
Time Held (%)	8	7	-	2	3	-	14	12	-
Aircraft Held (%)	47	43	-	23	25	-	33	27	-
Schedule Delay (sec)	117	120	-	68	95	<.01	74	56	-
Schedule Ratio (%)	119	119	-	138	145	<.01	103	100	-
<u>Orderliness</u>									
Mean Spacing (sec.)	99.3	80.0	-	101.6	102.7	-	113.6	96.0	-
Smoothing	-0.79	-0.65	-	-0.14	-0.24	<.05	-0.40	-0.45	-
<u>Cost</u>									
Fuel Consumption	769.1	373.6	<.01						

* The significance of the differences between the means shown was determined by an analysis of variance.

TABLE 3

Traffic Distribution Effect on System Performance

Measure	Total System				Conversion Control Subsystem				Local Control Subsystem			
	Equal	North	South	Sig.*	Equal	North	South	Sig.*	Equal	North	South	Sig.*
Safety												
Collision Probability (%)	72	77	50	-	35	30	13	-	55	59	48	-
Expeditiousness												
Time Held (%)	7	8	7	-	2	3	2	-	12	14	13	-
Aircraft Held (%)	39	50	46	<.05	19	29	24	-	29	32	30	-
Schedule Delay (sec.)	122	121	112	-	80	92	73	<.05	70	68	57	-
Schedule Ratio (%)	120	120	118	-	141	146	139	<.01	100	102	103	
Orderliness												
Mean Spacing (sec.)	85.2	91.5	92.2	-	93.9	94.1	118.6	-	114.7	108.0	91.8	-
Smoothing	-0.66	-0.97	-0.53	-	-0.09	-0.26	-0.22	<.05	-0.46	-0.60	-0.22	<.05
Cost												
Fuel Consumption	520.8	578.3	614.9	-								

* The significance of the differences between the means shown and determined by an analysis of variance.

TABLE 4

Procedural Effect on System Performance

Measure	Total System			Conversion Control Subsystem			Local Control Subsystem		
	Fixed	Flexible	Sig.*	Fixed	Flexible	Sig.*	Fixed	Flexible	Sig.*
<u>Safety</u>									
Collision Probability(%)	68	63	-	20	33	-	62	45	-
Number of Violations	40	43	-	25	18	-	15	26	
<u>Expeditiousness</u>									
Time Held (%)	10	4	<.01	4	1	<.01	17	9	<.01
Aircraft Held (%)	57	33	<.01	36	12	<.01	36	24	<.01
Schedule Delay (sec.)	125	112	-	76	87	<.05	67	63	-
Schedule Ratio (%)	119	119	-	139	145	<.01	100	103	-
Time in Buffer (min)	4.05	2.42	<.01						
Transition Time (sec.)				701.4	710.4				
<u>Orderliness</u>									
Mean Spacing (sec.)	103.5	75.7	-	114.4	90.0	-	126.6	83.1	<.01
Smoothing	-0.93	-0.51	<.01	-0.21	-0.17	-	-0.55	-0.29	<.05
<u>Cost</u>									
Fuel Consumption	593.7	548.9							

* The significance of the differences between the means shown was determined by an analysis of variance.

6.2. Traffic Variables

Air traffic control consists of three phases: the control of traffic on the ground at an airport; the control of traffic en route from one airport complex to another; and the control of traffic within the airport complex between the en route phase and the ground phase. The latter phase, designated terminal control, consists of two major functions: the control of aircraft in transition between the relatively stable conditions of en route flights and the final phases of landing or initial phases of takeoff; and the control of aircraft in the immediate vicinity of the runways.

The mission of a terminal air traffic control system is to make the most efficient use of the airspace under its jurisdiction so as to provide for the needs of all the potential users of that airspace, at the same time insuring the safe separation of the aircraft under its control. Efficient use of airspace means that aircraft will be scheduled over the shortest routes available, in as rapid and orderly a way as possible, and so that the cost of flying (mainly fuel consumption) will be minimized. The orderliness of control has to do with optimal sequencing of aircraft with widely differing performance characteristics, from high-speed military or commercial jets to single-engine sport planes and heliocopters. All classes of flyers have a right to efficient direction and control from the system.

Of all the criteria of system proficiency, safety is the most important. In the existing air traffic control system, the Federal Aviation Agency has established strict standards for maintaining separation in time and space between aircraft. Unfortunately the criteria of safety, expeditiousness, and orderliness of traffic handling, and the democratization of the airspace are not all compatible. The subjects were instructed to achieve the prescribed safety standards and only within these limits to optimize the other criteria.

If we ignore the crew variable in considering the effect of the traffic variables* on system performance in general we see, in Tables 2 and 3, that the system was relatively insensitive to variations in either distribution or composition of traffic. Again, most of the differences in performance occur in expeditious handling of traffic, and primarily by the conversion control subsystem.

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* In practice the different input rates proved indistinguishable. As a result, the problem periods representing different values of this variable were analyzed as replications of the other variables.

There is a striking similarity between the effects of these variables on the performance of the local control subsystem and the total system. If the local control subsystem performs well on a particular measure under a particular traffic configuration, the total system responds similarly. If we consider the measures on Tables 2 and 3, we find that this effect occurs 18 out of 22 times. This suggests that in the TATC system the local control subsystem made the major contribution to total system performance. This result is surprising if one considers the limited amount of airspace controlled by the local control subsystem, the relatively shorter time, compared to the conversion control subsystem, during which it exercised control over each aircraft, and the relatively small number of control options available to the local control subsystem.

6.3. Scheduling Variable

One of the most interesting results from the standpoint of future investigations was due to the effects of the scheduling variable. Systems which command or control the actions of other systems usually make schedules or plans for the disposition and utilization of the resources of the controlled system. Military commanders make war plans, business managers make production schedules, etc. One important aspect of these plans is that they make explicit a sequence of events which are to occur at particular times.

For the air traffic control system this sequence of events is the traffic schedule by means of which the control system insures the safe, expeditious and orderly handling of traffic. Traffic schedules are composed of flight plans which indicate the predicted locations of aircraft at particular times in the future. The essence of air traffic control is the establishment and maintenance of schedules. To perform this function, the control system should be able to accept all aircraft input to it, assign a flight plan to each, monitor how well each aircraft conforms to its schedule, and, if deviations occur because of either drift or emergency conditions, to readjust the schedule.

The scheduling variable was introduced in an attempt to determine whether a controller could schedule and control traffic in the terminal area without benefit of complete flight plans. The variable consisted of two sets of operating rules which differed in the degree of formal scheduling of the air traffic which was imposed on the controllers. Under one set of rules, the "pre-planned" condition, the controllers were provided with a complete flight plan for each aircraft, and no path deviation was permitted. Under the other set of rules, the "flexible" condition, only the entry and exit points in the terminal complex were given, and the operators had to

organize the traffic themselves by scheduling and routing aircraft according to the exigencies of the situation as it changed from moment to moment.

The operating rules for flexibility of scheduling were presumed to affect only the conversion control subsystem, although the effects of this variable upon total system and local control subsystem performance are also shown in Table 4. However, only the performance of the conversion control subsystem will be discussed.

The results indicate that when the conversion control subsystem was able to schedule the routes of aircraft according to flexible flight scheduling rules, it handled the traffic more expeditiously than when it had to conform to fixed schedule flight rules. Under fixed scheduling rules, 4 per cent of the aircraft spent time holding as compared to 1 per cent under flexible scheduling rules; under fixed rules 36 per cent of the aircraft were held at any time as compared to 12 per cent under flexible rules. These reductions are both significant and occurred with no compromise in safety. Although the collision probability measure showed an increase, the number of violations were reduced. Also, the traffic seemed to be controlled in a more orderly fashion.

As far as schedule accommodation is concerned, however, this effect is reversed. Under flexible scheduling rules, approximately 11 seconds per aircraft is added to the minimum schedule; this shows up also in the schedule ratio. An increase of 9 seconds in the average transition time per aircraft provides an additional clue concerning the apparent contradiction in these results.

To maintain adequate separation between aircraft and still impose little delay on their progress, the controllers seem to have assigned them to routes which were slightly longer than the most direct path. In other words, to accommodate the exigencies of the traffic environment, the controllers were trading space for time.

6.4. Contoller-Computer Interaction

One of the objectives of the TATC test was to uncover and study problems involved in the interaction between the operator and the computer while performing air traffic control operations. The initial system configuration was intended to assist the controller in doing his job by automating some of his functions. These functions varied among the different positions but we can identify four general areas of computer assistance: display generation; status and record keeping; conflict prediction; and monitoring.

Our observations of the system during the test led to the subjective conclusion that, although the computer did provide some degree of assistance, in general the amount of information which the controller had to insert exceeded the information which he received in return. At the conclusion of the test, an analysis of the conversion control subsystem led to the estimate that the conversion controller supplied about 4 times as much information as he received, or, stated another way, he received back about 25 per cent as much information as he supplied.

Whether this relationship materially affected the capability of the operator to control air traffic could not be determined from these preliminary test runs. The measure of information interchange seems to be too simple a criterion upon which to evaluate such questions of allocation of function, organization and display of information, and requirements for information insertion by the human. These are matters for future investigation. If there are to be humans in a control system, a primary question seems to be how to reduce their operating load so that they can perform their assigned functions with the degree of proficiency required to achieve the system mission.

7. DISCUSSION

The TATC project represents an attempt to apply and evaluate a particular model for studying the operations of a class of systems usually identified as command-control, information-processing, and decision-making.

Such systems characteristically operate in non-deterministic or emergent environments. They charactistically accept and process large amounts of rapidly changing data, make decisions based on these data, and issue command instructions which modify a controllable environment while conforming to a complex set of criteria. Generally these systems include computers, people, and mechanisms by which they can communicate within the system and with the outside world. Their successful design and operation usually depends upon the solution of problems of information transmission between the computer and the man.

These systems usually are so large and complex that it is difficult to study their operations under real-life conditions. The classical scientific technique in such a situation is to choose one aspect of system operations, small enough to be controllable in the laboratory, and study it. The method used in the TATC project is different. It seeks to reproduce in the laboratory a large portion of the system consisting of interrelated functions, to generate an environment which is as similar as possible to the real-life system environment, and to study the operations of the laboratory system in that environment.

7.1. Was the Test a Success?

The objectives of the system test were limited: to enable the researchers to gain familiarity with the system by observing it and to provide information which could be used for redesign purposes. We wanted to find out whether the initial configuration we had designed would work: whether it could actually control air traffic in a simulated environment, whether its performance would be affected by certain traffic conditions and procedural modifications, and whether problems of information interchange between the computer programs and the operators could be identified. With regard to these aims, the test was successful.

However, the test of an initial laboratory system configuration was part of a larger research project with broader objectives: to learn how to design and simulate systems in the laboratory and to identify questions for future research. The remainder of the discussion will deal with these objectives.

7.2. Design and Simulation

The design of a laboratory system as complex as the TATC System presents most, if not all, of the problems which must be solved by the designer of a real system operating in the field. The development of this system provided a good exercise in the art of system design which might well be expanded to provide a useful training device for designers. The cost of making errors under these conditions is extremely small in comparison to the cost of similar errors in designing real systems.

One of the most important problems identified during the design and development process was the difficulty of communication among engineers, programmers, and human factors personnel. To alleviate this situation we developed an inexpensive and rapid method of simulating the operations of the desired system and, in a series of games, "played through" all of the functions which the controllers and the computer were required to perform together. This technique provided a common referent experience and was used to generate a common task language which facilitated communication among the participants. This technique, which we call "schematic simulation," is discussed in more detail in TM-639/005/00.

We found that it was extremely difficult to standardize and control the activities of the people who operated the embedding system. They introduced too much unpredictable variability in the system environment, thus making it difficult to reproduce planned stimulus conditions from run to run. To the extent that rules can be written for the operation of the embedding agencies, it seems desirable to automate these functions. The

resulting decrease in flexibility in providing inputs to the laboratory system is compensated for by the achievement of greater control over environmental conditions.

We also produced an important methodological tool for studying complex laboratory systems: the technique of data regeneration. During the operation of the system, a set of initial conditions is recorded. Then a complete record is made of all keyboard interventions. Since the environment was controlled directly or indirectly only through these keyboard interventions, they constitute a complete and unambiguous record of the performance of the system. At a later time, these recorded keyboard insertions can be "played back" through the original system computer programs to regenerate all of the data that existed during the operations.

7.3. Research Questions

By operating the TATC system in the laboratory, we were able to identify several questions for future research. The results show that the markedly different ability of each crew to operate as a team affected the performance of the system; that system performance was relatively insensitive to the variations in traffic conditions, and that effective air traffic control could be conducted under flexible scheduling rules. What was there about the design of the system and its operation which could account for these results?

The experimenters predicted that Crew A would perform better than Crew B, and in general this prediction was upheld, although the differences in performance reach the accepted level of statistical significance only for the expeditious handling of traffic. It is no surprise that the better team was able to operate the system better. However, we may conjecture that this phenomenon may occur only in systems which are so designed as to make maximal use of the adaptive capabilities of the personnel subsystem; that is, in systems which are designed so that people can use the equipment and programs in new and different ways to suit the changing demands of the environment. One of the ways to do this is to provide the operators with information by which they can predict or recognize the effect of their actions upon the performance of other operators and upon total system performance. When a system is designed in this way, "functional visibility" is increased.* A question for future research might be: What is the effect of functional visibility on crew performance?

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* Functional visibility in systems is described by L. Alexander, et.al. "The effectiveness of knowledge of results in a military system-training program," J. Appl. Psychol., 1962, 46, 202-211.

The results also showed that the operators could use the system adaptively and could conduct air traffic control under flexible scheduling rules. Flexible scheduling procedures were introduced because we felt that rigid scheduling of flight plans might be restrictive in the relatively confined airspace available in the terminal area. We wanted to see if the operators could use the system to adapt flight schedules to the traffic exigencies which might arise. There are three aspects of scheduling which will have to be considered: the generation of schedules; the monitoring of the air traffic to predict and detect potentially serious deviations from schedules; and the resolution of these deviations by schedule readjustment. We do not propose that the entire scheduling function should be done by the humans in the system, but the finding that the system could operate under flexible scheduling procedures opens the door to a systematic investigation of the question: How can the capabilities of the man and the computer be combined to perform a complex scheduling function?

System performance was relatively insensitive to variations in the geographic distribution of traffic and in the heterogeneity of the traffic samples. This may have resulted from the ability of the crews to adapt their control procedures easily to the traffic variations. However, a simpler question should be tested first: Were these results due to a relatively low traffic load and to a restricted range of values of the traffic variables?

The methods used in the TATC project constitute a relatively new technique in system research. Certainly these methods are not as precise as those of classical research. Even so, the laboratory technique we have used seems to be the only one available for controlled study of intact man-machine information-processing systems. In order to achieve precision, new experimental design and statistical analysis tools will have to be developed.

There seem to be four main problems involved in the development and application of this method for studying systems: How does one simulate, manipulate, and control the complex environments of laboratory systems? How does one collect meaningful data regarding the performance of the system as a whole and especially as regards how system performance relates to the performance of the subsystem and individual components? How does one quickly and economically modify the component parts, their functions and interrelations so that a wide variety of configurations can be examined? And would the coordinate use of computer models assist in the development of theories of system performance and in the testing of hypotheses derived from these theories?

8. SUMMARY

The TATC project represents an attempt to produce in the laboratory the phenomena which occur in man-machine, information-processing systems. The essential aspect of the procedure is to create the complex environment within which such systems operate, to manipulate this environment, and to observe how the system responds in an effort to achieve its mission. The instrument which makes this technique possible is the high-speed digital computer, for only through its use can these complex environments be simulated, manipulated, and controlled.

We believe, on the basis of our experience with TATC, that significant system phenomena can be studied in the laboratory thereby contributing to the development of a science of systems.

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System Development Corporation,
Santa Monica, California
TEST RESULTS OF THE TERMINAL AIR
TRAFFIC CONTROL LABORATORY SYSTEM.
Scientific rept., TM-639/004/00, by
A. S. Cooperband, L. T. Alexander,
H. S. Schmitz. 23 September 1963,
27p., 2 figs., 4 tables

Unclassified report

DESCRIPTORS: Air Traffic Control Systems.

States that the TATC (Terminal Air Traffic Control) project attempts to produce in the laboratory the phenomena

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which occur in man-machine, information-processing systems. Reports that the essential aspect of the procedure is to create the complex environment within which such systems operate, to manipulate this environment, and to observe how the system responds in an effort to achieve its mission. Points out that the high-speed digital computer makes this technique possible, for only through its use can these complex environments be simulated, manipulated, and controlled. Concludes that, on the basis of experience with TATC, significant system phenomena can be studied in the laboratory thereby contributing to the development of a science of systems.

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